PEARSON

PHYSICS

WESTERN AUSTRALIA

STUDENT BOOK

11

Contents

UNIT 1 Thermal, nuclear and electrical physics

AREA OF STUDY 1

Heating processes

CHAPTER 1 **Heating processes** **3**
1.1 Heat and temperature 4
1.2 Specific heat capacity 11
1.3 Latent heat 15
1.4 Heating and cooling 21
Chapter review **25**

CHAPTER 2 **Moving heat around** **27**
2.1 Work and efficiency 28
2.2 Conduction 32
2.3 Convection 36
2.4 Radiation 39
Chapter review **43**

AREA OF STUDY 2

Ionising radiation and nuclear reactions

CHAPTER 3 **Particles in the nucleus** **45**
3.1 Atoms, isotopes and radioisotopes 46
3.2 Radioactivity 55
3.3 Properties of alpha, beta and gamma radiation 62
3.4 Half-life and decay series 68
3.5 Radiation doses and effects on humans 75
Chapter review **85**

CHAPTER 4 **Fission and fusion** **87**
4.1 Nuclear fission and energy 88
4.2 Chain reactions and nuclear reactors 96
4.3 Nuclear fusion 104
Chapter review **111**

AREA OF STUDY 3

Electrical circuits

CHAPTER 5 **Electrical physics** **113**
5.1 Behaviour of charged particles 114
5.2 Energy in electric circuits 119
5.3 Electric current and circuits 124
5.4 Resistance 132
5.5 Series and parallel circuits 142
5.6 Electrical safety 157
Chapter review **164**

Unit 1 Review **167**

UNIT 2 Linear motion and waves

AREA OF STUDY 4

Linear motion and force

CHAPTER 6 **Scalars and vectors** **173**
6.1 Scalars and vectors 174
6.2 Adding vectors in one and two dimensions 181
6.3 Subtracting vectors in one and two dimensions 187
6.4 Vector components 193
Chapter review **196**

CHAPTER 7 **Linear motion** **197**
7.1 Displacement, speed and velocity 198
7.2 Acceleration 208
7.3 Graphing position, velocity and acceleration over time 213
7.4 Equations for uniform acceleration 226
7.5 Vertical motion 232
Chapter review **239**

CHAPTER 8 **Momentum and forces** **243**
8.1 Momentum and conservation of momentum 244
8.2 Change in momentum and impulse 251
8.3 Newton's first law 254
8.4 Newton's second law 263
8.5 Newton's third law 271
8.6 Impulse and force 277
8.7 Mass and weight 287
Chapter review **291**

CHAPTER 9 **Work, energy and power** **293**
9.1 Energy and work 294
9.2 Kinetic energy 304
9.3 Elastic and inelastic collisions 309
9.4 Gravitational potential energy 313
9.5 Law of conservation of energy 318
9.6 Power 327
Chapter review **330**

AREA OF STUDY 5

Waves

CHAPTER 10 **The nature of waves** **332**
10.1 Longitudinal and transverse waves 334
10.2 Representing waves 339
10.3 Wave behaviours—reflection, refraction and diffraction 348
10.4 Wave interactions—superposition, interference and resonance 361
10.5 Standing waves and harmonics 367
10.6 Wave intensity and applications of wave properties 380
Chapter review **388**

AREA OF STUDY 6

Science inquiry skills

CHAPTER 11 **Practical investigation** **390**
11.1 Designing and planning the investigation 392
11.2 Conducting investigations, and recording and presenting data 400
11.3 Discussing investigations and drawing evidence-based conclusions 407
Chapter review **413**

Unit 2 Review **414**

APPENDIX A SI units **417**
APPENDIX B Understanding measurement **419**
APPENDIX C Mathematical skills for physics ATAR **430**
ANSWERS **450**
GLOSSARY **463**
INDEX **467**

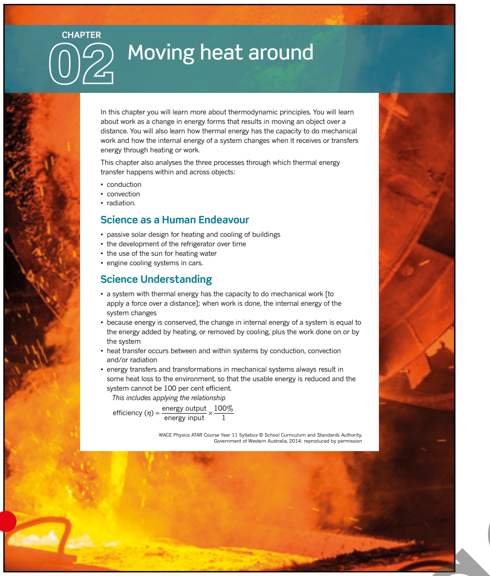
How to use this book

Pearson Physics 11 Western Australia

Pearson Physics 11 Western Australia has been written to the *WACE Physics ATAR Course, Year 11 Syllabus 2014*. Each chapter is clearly divided into manageable sections of work. Best practice literacy and instructional design are combined with high quality, relevant photos and illustrations. Explore how to use this book below.

Chapter opening page

The chapter opening page links the syllabus to the chapter content. Science Understanding and Science as a Human Endeavour addressed in the chapter is clearly listed.



CHAPTER 02 Moving heat around

In this chapter you will learn more about thermodynamic principles. You will learn about work as a change in energy forms that results in moving an object over a distance. You will also learn how thermal energy has the capacity to do mechanical work and how the internal energy of a system changes when it receives or transfers energy through heating or work.

This chapter also analyses the three processes through which thermal energy transfer happens within and across objects:

- conduction
- convection
- radiation.

Science as a Human Endeavour

- passive solar design for heating and cooling of buildings
- the development of the refrigerator over time
- the use of the sun for heating water
- engine cooling systems in cars.

Science Understanding

- a system with thermal energy has the capacity to do mechanical work [to apply a force over a distance]; when work is done, the internal energy of the system changes
- because energy is conserved, the change in internal energy of a system is equal to the energy added by heating, or removed by cooling, plus the work done on or by the system
- heat transfer occurs between and within systems by conduction, convection and/or radiation
- energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the usable energy is reduced and the system cannot be 100 per cent efficient.

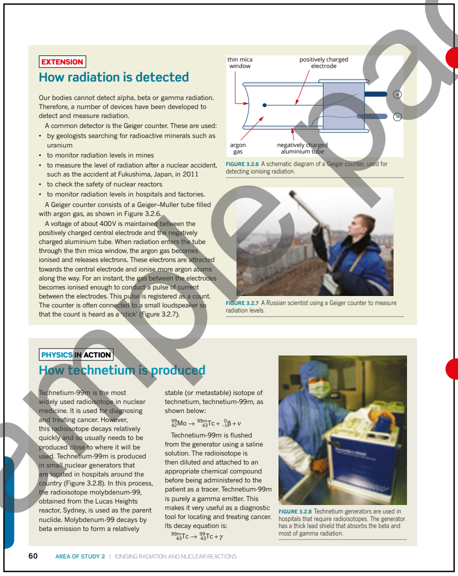
This includes applying the relationship

$$\text{efficiency } (\eta) = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

WACE Physics ATAR Course Year 11 Syllabus © School Curriculum and Standards Authority, Government of Western Australia, 2014; reproduced by permission

EXTENSION

Extension boxes include material that goes beyond the core content of the syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.



EXTENSION

How radiation is detected

Our bodies cannot detect alpha, beta or gamma radiation. Therefore, a number of devices have been developed to detect and measure radiation.

A common detector is the Geiger counter. These are used:

- by geologists searching for radioactive minerals such as uranium
- to monitor radiation levels in mines
- to measure the level of radiation after a nuclear accident, such as the accident at Fukushima, Japan, in 2011
- to check the safety of nuclear reactors
- to monitor radiation levels in hospitals and factories.

A Geiger counter consists of a Geiger–Muller tube filled with argon gas, as shown in Figure 3.2.6.

A voltage of about 400V is maintained between the positively charged central electrode and the negatively charged aluminium tube. When radiation enters the tube through the thin mica window, the argon gas becomes ionised and releases electrons. These electrons are attracted towards the central electrode and ionise more argon atoms along the way. For an instant, the gas between the electrodes becomes ionised enough to conduct a pulse of current between the electrodes. This pulse is registered as a count. The counter is often connected to a small loudspeaker so that the count is heard as a 'click' (Figure 3.2.7).

FIGURE 3.2.6 A schematic diagram of a Geiger counter, used for detecting ionising radiation.

FIGURE 3.2.7 A Russian scientist using a Geiger counter to measure radiation levels.

PHYSICS IN ACTION

How technetium is produced

Technetium-99m is the most widely used radioisotope in nuclear medicine. It is used for diagnosing and treating cancer. However, this radioisotope decays relatively quickly and so usually needs to be produced close to where it will be used. Technetium-99m is produced in small nuclear generators that are located in hospitals around the country (Figure 3.2.8). In this process, the radioisotope molybdenum-99, obtained from the Lucas Heights reactor, Sydney, is used as the parent nuclide. Molybdenum-99 decays by beta emission to form a relatively stable (or metastable) isotope of technetium, technetium-99m, as shown below:

$${}^{99}_{42}\text{Mo} \rightarrow {}^{99m}_{43}\text{Tc} + {}^{0}_{-1}\beta + \nu$$

Technetium-99m is flushed from the generator using a saline solution. The radioisotope is then diluted and attached to an appropriate chemical compound before being administered to the patient as a tracer. Technetium-99m is purely a gamma emitter. This makes it very useful as a diagnostic tool for locating and treating cancer. Its decay equation is:

$${}^{99m}_{43}\text{Tc} \rightarrow {}^{99}_{43}\text{Tc} + \gamma$$

FIGURE 3.2.8 Technetium generators are used in hospitals that require radioisotopes. The generator has a thick lead shield that absorbs the beta and most of gamma radiation.

60 AREA OF STUDY 2 | IONISING RADIATION AND NUCLEAR REACTIONS

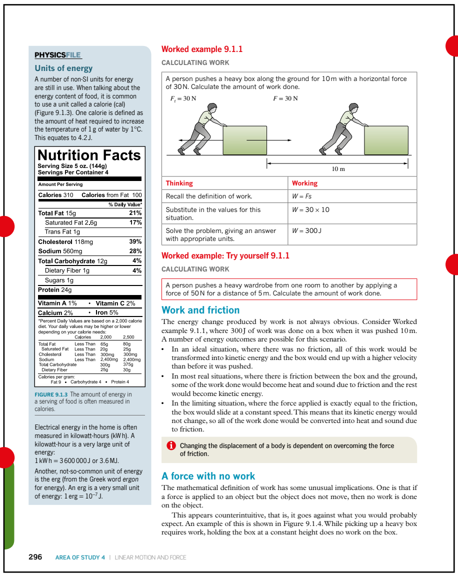
PHYSICS IN ACTION

Physics in Action boxes place physics in an applied situation or relevant context and encourage students to think about the development of physics and the use and influence of physics in society.

Worked examples

Worked examples are set out in steps that show both thinking and working. This enhances student understanding by clearly linking underlying logic to the relevant calculations.

Each Worked example is followed by a Worked example: Try yourself. This mirror problem allows students to immediately test their understanding.



PHYSICSFILE

Units of energy

A number of non-SI units for energy are still in use. When talking about the energy content of food, it is common to use a unit called a calorie (cal) (Figure 9.1.3). One calorie is defined as the amount of heat required to increase the temperature of 1 g of water by 1°C. This equates to 4.2J.

Nutrition Facts
Serving Size 5 oz. (144g)
Servings Per Container 4

Amount Per Serving	
Calories 310 **Calories** from Fat 100	
	% Daily Value*
Total Fat 15g	**21%**
Saturated Fat 2.6g	**17%**
Trans Fat 1g	
Cholesterol 118mg	**39%**
Sodium 560mg	**28%**
Total Carbohydrate 12g	**4%**
Dietary Fiber 1g	**4%**
Sugars 1g	
Protein 24g	
Vitamin A 1% • **Vitamin C** 2%	
Calcium 2% • **Iron** 5%	

*Percent Daily Values are based on a 2,000 calorie diet. Your daily values may be higher or lower depending on your calorie needs:

	Calories	2,000	2,500
Total Fat	Less Than	65g	80g
Saturated Fat	Less Than	20g	25g
Cholesterol	Less Than	300mg	300mg
Sodium	Less Than	2,400mg	2,400mg
Total Carbohydrate		300g	375g
Dietary Fiber		25g	30g

Calories per gram:
Fat 9 • Carbohydrate 4 • Protein 4

FIGURE 9.1.3 The amount of energy in a serving of food is often measured in calories.

Electrical energy in the home is often measured in kilowatt-hours (kWh). A kilowatt-hour is a very large unit of energy:
1 kWh = 3 600 000 J or 3.6 MJ.

Another, not-so-common unit of energy is the erg (from the Greek word *ergon* for energy). An erg is a very small unit of energy: 1 erg = 10^{-7} J.

Worked example 9.1.1

CALCULATING WORK

A person pushes a heavy box along the ground for 10 m with a horizontal force of 30 N. Calculate the amount of work done.

Thinking	Working
Recall the definition of work.	$W = Fs$
Substitute in the values for this situation.	$W = 30 \times 10$
Solve the problem, giving an answer with appropriate units.	$W = 300$ J

Worked example: Try yourself 9.1.1

CALCULATING WORK

A person pushes a heavy wardrobe from one room to another by applying a force of 50 N for a distance of 5 m. Calculate the amount of work done.

Work and friction

The energy change produced by work is not always obvious. Consider Worked example 9.1.1, where 300 J of work was done on a box when it was pushed 10 m. A number of energy outcomes are possible for this scenario.

- In an ideal situation, where there was no friction, all of this work would be transformed into kinetic energy and the box would end up with a higher velocity than before it was pushed.
- In most real situations, where there is friction between the box and the ground, some of the work done would become heat and sound due to friction and the rest would become kinetic energy.
- In the limiting situation, where the force applied is exactly equal to the friction, the box would slide at a constant speed. This means that its kinetic energy would not change, so all of the work done would be converted into heat and sound due to friction.

ℹ Changing the displacement of a body is dependent on overcoming the force of friction.

A force with no work

The mathematical definition of work has some unusual implications. One is that if a force is applied to an object but the object does not move, then no work is done on the object.

This appears counterintuitive, that is, it goes against what you would probably expect. An example of this is shown in Figure 9.1.4. While picking up a heavy box requires work, holding the box at a constant height does no work on the box.

296 AREA OF STUDY 4 | LINEAR MOTION AND FORCE

PHYSICSFILE

PhysicsFile includes a range of interesting information and real world examples.

ℹ Highlight box

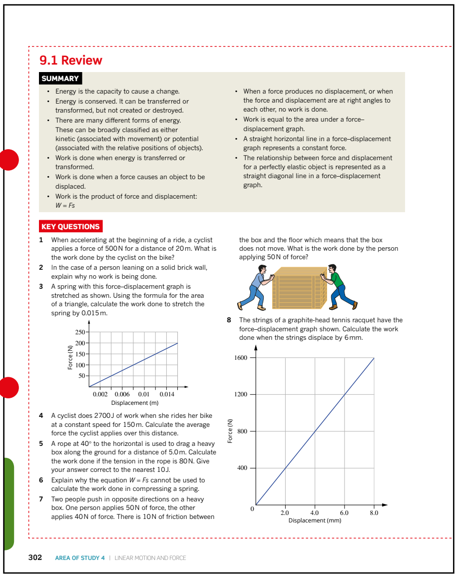
Focuses students' attention on important information such as key definitions, formulae and summary points.

Section summary

Each section includes a summary to assist students consolidate key points and concepts.

Section review questions

Each section finishes with questions to test students' understanding and ability to recall the key concepts of the section.



9.1 Review

SUMMARY

- Energy is the capacity to cause a change.
- Energy is conserved. It can be transferred or transformed, but not created or destroyed.
- There are many different forms of energy. These can be broadly classified as either kinetic (associated with movement) or potential (associated with the relative positions of objects).
- Work is done when energy is transferred or transformed.
- Work is done when a force causes an object to be displaced.
- Work is the product of force and displacement: $W = Fs$
- When a force produces no displacement, or when the force and displacement are at right angles to each other, no work is done.
- Work is equal to the area under a force–displacement graph.
- A straight horizontal line in a force–displacement graph represents a constant force.
- The relationship between force and displacement for a perfectly elastic object is represented as a straight diagonal line in a force–displacement graph.

KEY QUESTIONS

1 When accelerating at the beginning of a ride, a cyclist applies a force of 500 N for a distance of 20 m. What is the work done by the cyclist on the bike?

2 In the case of a person leaning on a solid brick wall, explain why no work is being done.

3 A spring with this force–displacement graph is stretched as shown. Using the formula for the area of a triangle, calculate the work done to stretch the spring by 0.015 m.

4 A cyclist does 2700 J of work when she rides her bike at a constant speed for 150 m. Calculate the average force the cyclist applies over this distance.

5 A rope at 40° to the horizontal is used to drag a heavy box along the ground for a distance of 5.0 m. Calculate the work done if the tension in the rope is 80 N. Give your answer correct to the nearest 10 J.

6 Explain why the equation $W = Fs$ cannot be used to calculate the work done in compressing a spring.

7 Two people push in opposite directions on a heavy box. One person applies 50 N of force, the other applies 40 N of force. There is 10 N of friction between the box and the floor which means that the box does not move. What is the work done by the person applying 50 N of force?

8 The strings of a graphite-head tennis racquet have the force–displacement graph shown. Calculate the work done when the strings displace by 6 mm.

302 AREA OF STUDY 4 | LINEAR MOTION AND FORCE

Chapter review

Each chapter finishes with a set of higher order questions to test students' ability to apply the knowledge gained from the chapter.

Chapter review

KEY TERMS

conservation of energy
conservation of mechanical energy
efficiency
elastic collision
gravitational potential energy
inelastic collision
kinetic energy
mechanical energy
power
transform
work

1 A car drives at a constant speed for 80 m. In order to overcome friction, its engine applies a force of 2000 N. Calculate the work done by the engine.

2 Estimate the total work shown in the following force–displacement graph, given that each grid square corresponds to 1 J.

3 A crane lifts a 200 kg load from the ground to a height of 30 m. What is the work done by the crane?

4 A person walks up a flight of 12 stairs. Each step is 240 mm long and 165 mm high. If the person has a mass of 60 kg and $g = 9.80\ \text{m s}^{-2}$, what is the total amount of work done against gravity?

5 If 4000 J is used to lift a 50.0 kg object with a constant velocity, what is the theoretical maximum height to which the object can be raised?

6 A pram is pushed by the handle, which is at an angle of 35° to the horizontal (the direction of motion). If 1200 J of work is done pushing the pram 20 m, with what force was the pram pushed?

7 A cricket ball with a mass of 160 g is bowled with a speed of 150 km h^{-1}. What is the kinetic energy of the cricket ball?

8 If a 1200 kg car has kinetic energy of 70 kJ, what is its speed?

9 The speed of an object is doubled. By how much does its kinetic energy increase?

10 A plumber (mass 88 kg) digs a ditch 40 cm deep. By how much does the plumber's gravitational potential energy change when he steps from the ground down into the ditch?

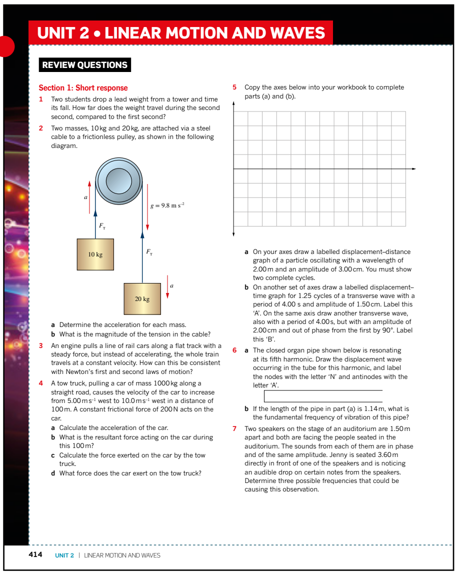
11 A football with a mass of 0.43 kg is kicked off the ground with a speed of 16 m s^{-1}. How fast will it be going when it hits the crossbar, which is 2.44 m above the ground?

12 A white billiard ball moving with a speed of 5.00 m s^{-1} strikes a stationary red billiard ball. After the collision, the white ball continues in the same direction at a speed of 1.00 m s^{-1}. The red ball rolls ahead of it (in the direction of the white ball's initial motion) with a speed of 4.00 m s^{-1}. Each ball has a mass of 160g. Determine the energy of the objects both before and after the collision, and state whether it was elastic or inelastic.

330 AREA OF STUDY 4 | LINEAR MOTION AND FORCE

Unit Review

Each unit finishes with a comprehensive set of exam-style questions, which assist students to draw together their knowledge and understanding and apply it to this style of question.



UNIT 2 • LINEAR MOTION AND WAVES

REVIEW QUESTIONS

Section 1: Short response

1 Two students drop a lead weight from a tower and time its fall. How far does the weight travel during the second second, compared to the first second?

2 Two masses, 10 kg and 20 kg, are attached via a steel cable to a frictionless pulley, as shown in the following diagram.

a Determine the acceleration for each mass.
b What is the magnitude of the tension in the cable?

3 An engine pulls a line of rail cars along a flat track with a steady force, but instead of accelerating, the whole train travels at a constant velocity. How can this be consistent with Newton's first and second laws of motion?

4 A tow truck, pulling a car of mass 1000 kg along a straight road, causes the velocity of the car to increase from 5.00 m s^{-1} west to 10.0 m s^{-1} west in a distance of 100 m. A constant frictional force of 200 N acts on the car.
a Calculate the acceleration of the car.
b What is the resultant force acting on the car during this 100 m?
c Calculate the force exerted on the car by the tow truck.
d What force does the car exert on the tow truck?

5 Copy the axes below into your workbook to complete parts (a) and (b).
a On your axes draw a labelled displacement–distance graph of a particle oscillating with a wavelength of 2.00 m and an amplitude of 3.00 cm. You must show two complete cycles.
b On another set of axes draw a labelled displacement–time graph for 1.25 cycles of a transverse wave with a period of 4.00 s and amplitude of 1.50 cm. Label this 'A'. On the same axis draw another transverse wave, also with a period of 4.00 s, but with an amplitude of 2.00 cm and out of phase from the first by 90°. Label this 'B'.

6 a The closed organ pipe shown below is resonating at its fifth harmonic. Draw the displacement wave occurring in the tube for this harmonic, and label the nodes with the letter 'N' and antinodes with the letter 'A'.
b If the length of the pipe in part (a) is 1.14 m, what is the fundamental frequency of vibration of this pipe?

7 Two speakers on the stage of an auditorium are 1.50 m apart and both are facing the people seated in the auditorium. The sounds from each of them are in phase and of the same amplitude. Jenny is seated 3.60 m directly in front of one of the speakers and is noticing an audible drop on certain notes from the speakers. Determine three possible frequencies that could be causing this observation.

414 UNIT 2 | LINEAR MOTION AND WAVES

Glossary

Key terms are shown in bold and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.

Glossary

A

absolute zero	The coldest possible temperature.
absorbed dose	The amount of ionising radiation absorbed per kilogram of irradiated material, measured in grays (Gy).
absorption	The taking up and storing of energy, such as radiation, light or sound, without it being reflected or transmitted. During absorption the energy may change from one form into another. When radiation strikes the electrons in an atom, the electrons move to a higher orbit or state of excitement by absorption of the radiation's energy.
acceleration	The rate of change of velocity. Acceleration is a vector quantity. The SI unit for acceleration is m s^{-2}.
activity	The number of nuclei of a radioactive substance that decay each second, measured in becquerels (Bq).
air pressure	The force per unit area exerted by air on an object; related to the density or the number of particles.
air resistance	The retarding force (drag) caused by collisions between air and moving objects.
alpha (α) particle	A particle consisting of two protons and two neutrons; ejected from the nucleus of a radioactive nuclide.
alternating current	In an alternating current (AC), electrons oscillate backwards and forwards around a mean position, as opposed to direct current (DC). Household power supplies usually operate at 240 V AC.
amplitude	The maximum displacement of a particle from the average or rest position.
angle of incidence	The angle an incident ray makes with the normal to the surface it strikes.
angle of reflection	The angle a reflected ray makes with the normal to the surface it strikes. Equal to the angle of incidence.
angle of refraction	The angle a refracted ray makes with the normal to the surface when it has travelled from one medium to another.
antineutrino	A neutral subatomic particle that interacts very weakly with other matter; the antimatter particle of neutrino.
antinode	Areas in a standing wave where complete constructive interference is happening.
artificial transmutation	The changing of one element or isotope into another. This happens during radioactive decay and during neutron bombardment in a nuclear reactor.
atomic number	The number of protons in a nucleus.

B

background radiation	The low level of ionising radiation that exists in the environment as a result of the Earth being radioactive.
beta (β) particle	An electron or positron; ejected from the nucleus of a radioactive nuclide.
binding energy	Energy required to split a nucleus into its separate nucleons.

C

centre of mass	A single point in an object where the mass can be considered to be 'concentrated' for the purposes of analysing motion.
chain reaction	A series of nuclear fissions that may be controlled or uncontrolled.
charge	A property of matter that causes electric effects. Protons have positive charge, electrons have negative charge and neutrons have no charge.
circuit breaker	A device that automatically switches off an excessive current by detecting the magnetic field associated with it.
collinear	Lying on the same straight line.
components	The components of a force are two vectors at right angles to each other that when added together will be equivalent to the original force.
compressions	Areas of high pressure in a wave.
conduction	The movement of energy (such as heat) from one object to another without the net movement of particles (atoms or molecules).
conductor	A substance, body or system that readily conducts heat, electricity, sound or light.
conservation of energy	The energy in a system before an interaction is exactly equal to the energy in the system after the interaction.
conservation of mechanical energy	The total mechanical energy in a system (i.e. the potential and kinetic energies) remains constant.
conserved	When a quantity that exists before an interaction is exactly equal to the quantity that exists after the interaction.
constructive interference	The process where two or more waves combine or superpose to reinforce each other. This occurs where the displacement of the individual waves is in the same direction so the amplitude is increased.
contact forces	Forces that exist when one object or material is touching another. Friction, drag and normal reaction forces are contact forces.
control rod	Material, commonly boron, steel or cadmium, that absorbs neutrons in a nuclear reactor.
controlled variable	A variable that must be kept constant during an investigation.
convection	A process of heat transfer through a gas or liquid by bulk motion of hotter material into a cooler region.
conventional current	A flow of positive electric charge. Conventional current is in the opposite direction to electron flow.
coolant	A substance, commonly water, carbon dioxide or liquid sodium, used to transfer thermal energy from the core of a nuclear reactor.
core	Part of a nuclear reactor where nuclear fission occurs and thermal energy is produced.
coulomb	The SI unit of charge; 1C is equivalent to the combined charge of 6.2×10^{18} protons.
crest	The maximum positive displacement reached when particles in a transverse wave are displaced upwards from the average position, or resting position.
critical angle	For refraction, the incident angle at which total internal reflection occurs. That is, the refracted angle is exactly 90° from the normal and lies along the interface between the two media.
critical mass	The minimum amount of enriched fissile material in the shape of a sphere that leads to a sustained fission reaction.
current	The net flow of electric charge. Current is measured in amperes (A) where 1 A = 1 C s^{-1}. By convention, electric current is assumed to flow from positive to negative.

D

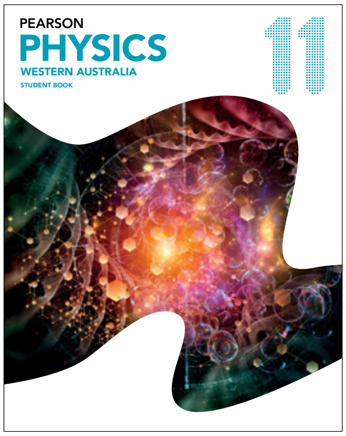
daughter nucleus	A nucleus on the product side of a nuclear equation; it results when a nucleus undergoes fission or radioactive decay.
decay series	A sequence of radioactive decays that results in the formation of a stable isotope.
dependent variable	The variable that may change in response to a change in the independent variable. On a graph, the dependent variable is plotted on the vertical axis.
destructive interference	The process in which two or more waves combine or superimpose to reduce the amplitude. This occurs where the displacement of the individual waves is in the opposite direction.
deuterium	An isotope of hydrogen with one proton and one neutron.
diffract	The process affecting light and other wave forms that causes a wave to spread out as it passes through a narrow aperture or past an edge.
diffuse	Spread out; for example, a wave reflecting off an irregular surface.
dimension	Space can be considered to consist of three length dimensions. These length dimensions are arranged at 90° to each other with their point of intersection being the origin. The position of an object can be defined in relation to its position along each of the three dimensions. Typically, these three dimensions are labelled *x*, *y* and *z*. However, up-down, left-right and backward-forward are also appropriate.
dimensional analysis	Using the units in a graph or formula to check that the derived term is correct.
direct current	In a direct current (DC), electrons travel in one direction only, as opposed to alternating current (AC). Batteries and electric cells provide direct current.
direction conventions	Standardised systems for describing the direction in which an object is travelling. The use of cardinal points of a compass (N, S, E and W) is an example of a direction convention.
displacement	An object's change in position, relative to its starting position and final position. Displacement does not consider the route the object took to change position, only where it started and where it ended. Displacement is a vector quantity. It is measured in metres (m) and given the symbol *s*.
distance travelled	How far an object travels during a particular motion or journey. Distance is a scalar value. Direction is not required when expressing magnitude. It is measured in metres (m) and given the symbol *d*.
Doppler effect	A change in the observed frequency of a wave, such as sound or light, that occurs when the source and observer are in motion relative to each other.
dose equivalent	A measure of the biological damage inflicted on a tissue due to absorption of a defined quantity of radiation. Dose equivalent measurements take into account the nature of the radiation applied. It is measured in sieverts (Sv).

GLOSSARY 463

Answers

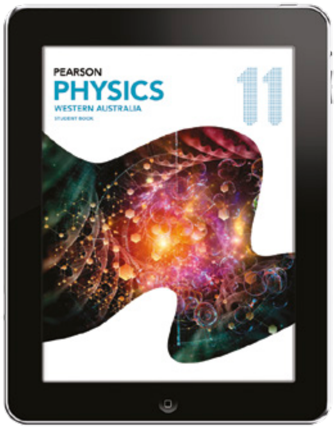
Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Worked examples: Try yourself, chapter review questions and Unit review questions are provided via *Pearson Physics 11 Western Australia Teacher Resource.*

Pearson Physics 11 Western Australia



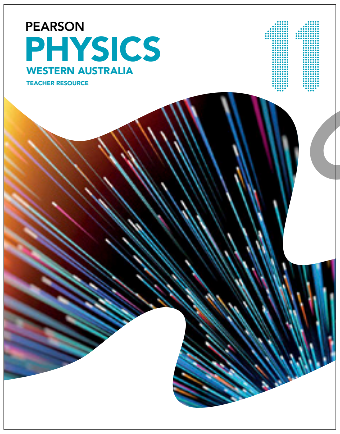
Student Book

Pearson Physics 11 Western Australia has been written to fully align with the *WACE Physics ATAR Course, Year 11 Syllabus 2014.* The series includes the very latest developments and applications of physics and incorporates best practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.



Reader+

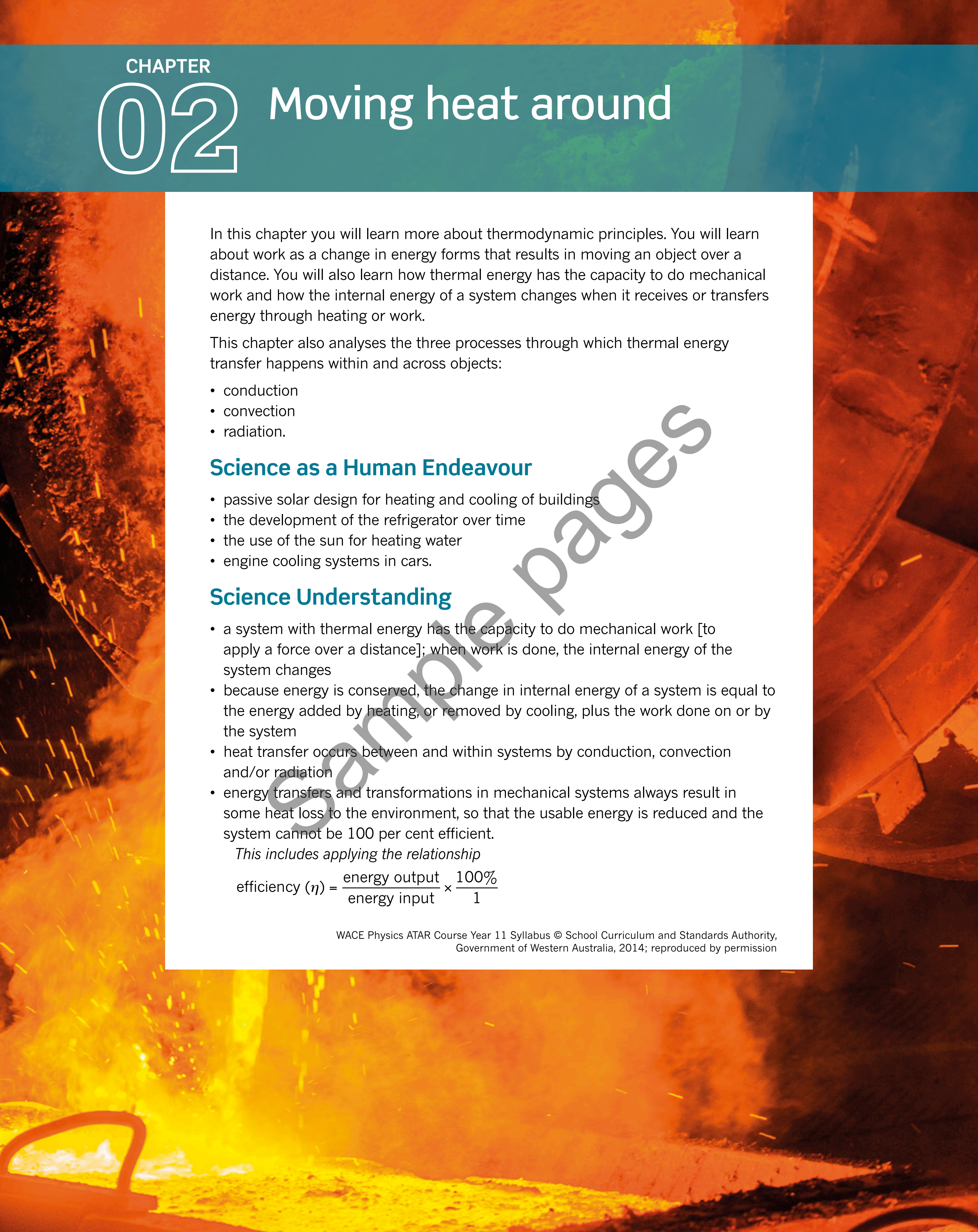
Pearson Reader+ lets you use the Student Book online or offline on any device. Pearson Reader+ includes interactive activities and videos to enhance learning and test understanding. The teacher version includes support material to assist planning and implementing the syllabus.



Teacher Resource

The *Pearson Physics 11 Western Australia Teacher Resource* consists of a print book and online resources, and provides comprehensive teacher support including teaching programs, fully worked solutions to all questions and chapter tests and practice exams.

Access digital resources at **pearsonplaces.com.au**
Browse and buy at **pearson.com.au**



CHAPTER 02 Moving heat around

In this chapter you will learn more about thermodynamic principles. You will learn about work as a change in energy forms that results in moving an object over a distance. You will also learn how thermal energy has the capacity to do mechanical work and how the internal energy of a system changes when it receives or transfers energy through heating or work.

This chapter also analyses the three processes through which thermal energy transfer happens within and across objects:

- conduction
- convection
- radiation.

Science as a Human Endeavour

- passive solar design for heating and cooling of buildings
- the development of the refrigerator over time
- the use of the sun for heating water
- engine cooling systems in cars.

Science Understanding

- a system with thermal energy has the capacity to do mechanical work [to apply a force over a distance]; when work is done, the internal energy of the system changes
- because energy is conserved, the change in internal energy of a system is equal to the energy added by heating, or removed by cooling, plus the work done on or by the system
- heat transfer occurs between and within systems by conduction, convection and/or radiation
- energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the usable energy is reduced and the system cannot be 100 per cent efficient.

  This includes applying the relationship

$$\text{efficiency } (\eta) = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

WACE Physics ATAR Course Year 11 Syllabus © School Curriculum and Standards Authority, Government of Western Australia, 2014; reproduced by permission

2.1 Work and efficiency

Most traditional power plants, such as that illustrated in Figure 2.1.1, use thermal energy to produce steam. The thermal energy comes from the burning of coal or the decay of a radioactive isotope. The steam produced does work turning turbines, which generate electricity. The capacity of thermal energy to do mechanical work is an important aspect in the study of heating processes.

FIGURE 2.1.1 Most power plants use thermal energy to produce steam. That steam does work turning turbines, which generate electricity.

ENERGY AND WORK

Energy is difficult to define, but can be described as the ability to do work. That means that energy has the potential to move objects over a distance.

Energy takes many different forms—for example, thermal, kinetic or potential. Despite the apparent differences in nature of the various forms of energy, any form of energy can be changed from one form to another. In order for any energy transformation to occur, say from heat to motion, work must be done. The work done on an object can be measured and, therefore, different types of energy can be compared by the work that they can do.

The work (W) done by a system, measured in joules (J), is calculated by multiplying the force of magnitude F (N) applied to an object that moves it a distance s (m) in the direction of the force:

$$W = Fs$$

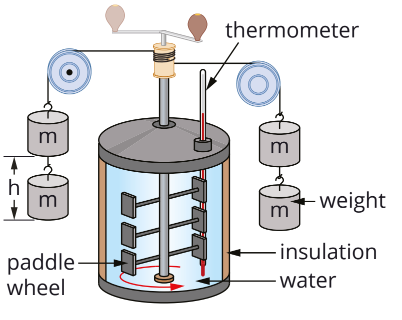


FIGURE 2.1.2 Joule's apparatus for investigating the heating effect of mechanical work allowed the transfer of heat energy to be measured and related to other forms of energy.

Mechanical energy to thermal energy

The experiments of James Prescott Joule (1818–89) were fundamental in understanding how mechanical work could transform mechanical energy into thermal energy. Joule noticed that stirring water could cause its temperature to rise. He designed a way to measure the relationship between the energy transferred when stirring the water and the change in temperature. A metal paddle wheel was rotated by falling masses and this churned the water around in an insulated can. Joule's original experimental set-up is shown in Figure 2.1.2.

The work done in the system used in Joule's experiment was calculated by multiplying the weight of the falling masses (which churned the water) by the distance they fell. The heat generated was calculated from the mass of the water and the temperature rise. Joule found that the same amount of mechanical work ($W = Fs$) always produced exactly the same amount of heating. This meant that heat was another form of energy, known now as thermal energy. Joule found that approximately 4.18 J of work was needed to raise the temperature of 1 g of water by 1°C, a figure now referred to as the specific heat capacity of water ($c = 4180\,\mathrm{J\,kg\,K^{-1}}$). The heat energy transferred (Q) by the transfer of mechanical energy to a mass m for a change in temperature of ΔT is thus equal to $Q = mc\Delta T$.

Thermal energy to mechanical energy

A system with thermal energy has the capacity to do mechanical work; that is, to apply a force that moves something. Through work, energy is transferred from one system to another. The system doing work will lose **internal energy**; the system on which work is done will gain internal energy. The change in internal energy of a system is equal to the energy added by heating or removed by cooling, plus the work done on or by the system.

The most common examples of thermal energy being used to do work are thermal power stations. Almost all traditional power plants (Figure 2.1.3) are thermal, including nuclear, coal, solar thermal electric and many natural gas power plants.

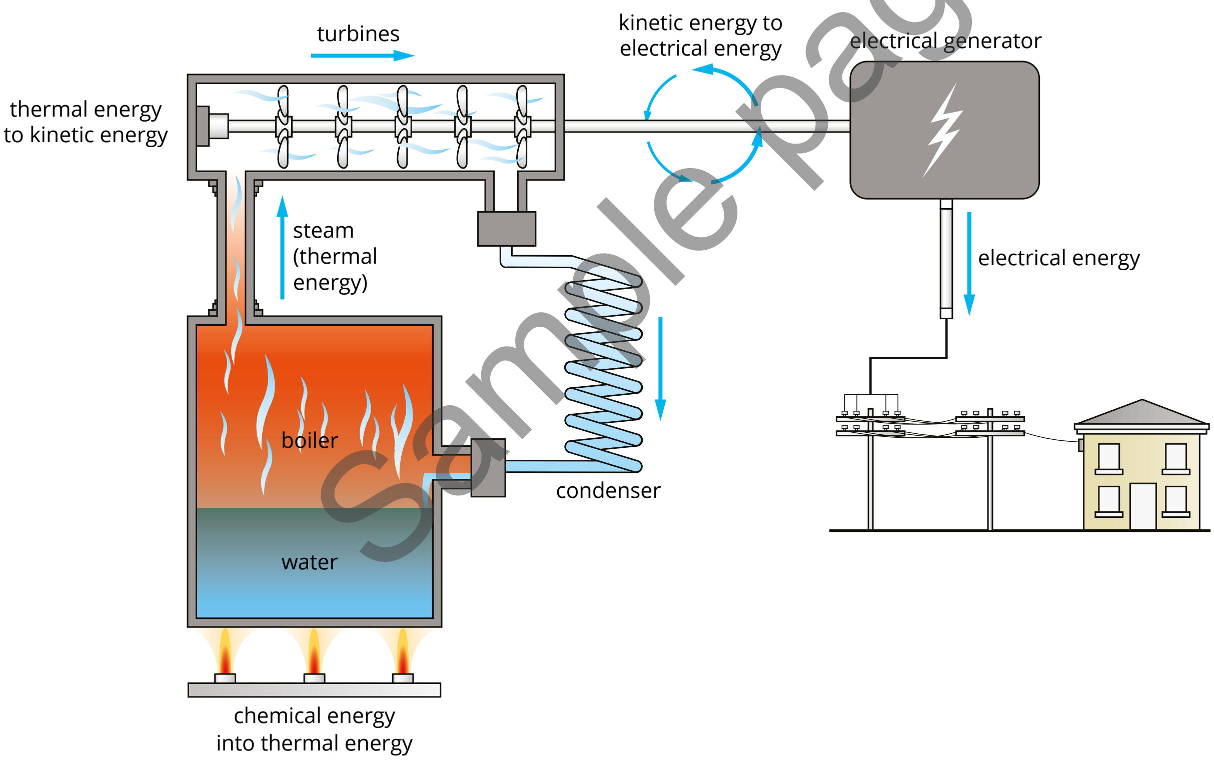


FIGURE 2.1.3 A thermal power station, which uses steam to drive turbines and generate electricity.

A thermal power station is a power plant that uses fuel to heat water to steam under high pressure. The steam performs mechanical work on steam turbines, which drive electrical generators. After steam passes through the turbine, it is condensed in a condenser and recycled to where it was heated.

Through this process, thermal power stations convert forms of heat energy into electrical energy. The greatest variation in the design of thermal power stations is due to the different fuels (mostly fossil fuels) used to heat the water.

Efficiency of energy transformations

In the real world, energy transformations, such as the ones described for a thermal power plant, are never perfect—there is always some energy lost. Because of this, for a system to continue operating (doing work), it must be constantly provided with energy. The percentage of energy that is effectively transformed by a system is called the efficiency of that device. A device operating at 45% efficiency converts 45% of its supplied energy into the useful new form. The other 55% is lost to the surroundings, usually as heat and/or sound. Table 2.1.1 shows the efficiencies of some devices.

The efficiency of a transformation from one energy form to another is expressed as:

$$\text{efficiency } (\eta) = \frac{\text{useful energy transformed}}{\text{total energy supplied}} \times 100\%$$

$$= \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

TABLE 2.1.1 Approximate efficiencies of some common things.

Device	Energy transformation	Efficiency (%)
electric motor	electric to kinetic	90
gas heater	chemical to thermal	75
incandescent light globe	electric to light	2
compact fluorescent light	electric to light	10
LED household light	electric to light	15
steam turbine	thermal to kinetic	45
coal-fired generator	chemical to electrical	30
high-efficiency solar cell	radiation to electrical	35
car engine	chemical to kinetic	25
open fireplace	chemical to thermal	15
human body	chemical to kinetic	25

Worked example 2.1.1

ENERGY EFFICIENCY

The energy input of a gas-fired power station is 1100 MJ. The electrical energy output is 300 MJ. What is the efficiency of the power station?

Thinking	Working
Recall the formula for efficiency of energy transformations.	$\text{efficiency } (\eta) = \frac{\text{energy output}}{\text{energy input}} \times 100\%$
Substitute the known values into the formula. Both values are in MJ, so there's no need to change them to J.	output = 300 MJ input = 1100 MJ $\text{efficiency } (\eta) = \frac{300}{1100} \times 100$
Calculate the answer.	efficiency = 27%

Worked example: Try yourself 2.1.1

ENERGY EFFICIENCY

An electric kettle uses 23.3 kJ of electrical energy as it boils a quantity of water. The efficiency of the kettle is 18%. How much electrical energy is used in actually boiling the water? Give your answer in kJ.

2.1 Review

SUMMARY

- When work is done, the internal energy of a system changes.
- A system with thermal energy has the capacity to do mechanical work.
- The mechanical work, W, done by a system is calculated by multiplying the force of magnitude F applied to an object that moves it a distance s in the direction of the force:

$$W = Fs$$

- The efficiency of a transformation from one energy form to another is given by:

$$\text{efficiency } (\eta) = \frac{\text{useful energy transformation}}{\text{total energy supplied}} \times 100\%$$

$$= \frac{\text{energy output}}{\text{energy input}} \times 100\%$$

KEY QUESTIONS

1 Identify all of the energy transformations that take place in a coal-fired electrical generator.

2 What caused a rise in temperature in the water in Joule's experiment?

3 How much work is done on an object of 4.5 kg when it is lifted vertically at a constant speed through a displacement of 6.0 m? (Use $g = 9.80\,\text{m s}^{-2}$.)

4 A student places a heating element and a paddle wheel apparatus in an insulated container of water. She calculates that the heater adds 2530 J of heat energy to the water, and the paddle wheel does 240 J of work on the water. Calculate the change in internal energy of the water.

The following information applies to questions 5 and 6.
A weightlifter raises a 100 kg mass 2.4 m above the ground in a weightlifting competition. After holding it for 3.0 s he places it back on the ground.

5 How much work has been done by the weightlifter in raising the mass? Use $g = 9.80\,\text{m s}^{-2}$ and give your answer to two significant figures.

6 How much additional work is done during the 3.0 s he holds it steady?

7 A particular model of reverse-cycle air conditioner produces 1.2 kW of useful heat from 4.8 kW of electrical energy. What is the efficiency of the air conditioner?

8 An electric drill uses 3.6 kJ of energy to drill a hole through a sheet of steel. The efficiency of the drill is 70%. How much electrical energy, in kJ, is used in actually making the hole?

9 A cook uses an egg beater on a warm chocolate sauce. If the cook does 845 J of work on the sauce while the warm sauce loses 1239 J of heat to the environment, what is the change in internal energy of the chocolate sauce?

10 A coal-fired generator has an efficiency of approximately 30%. If 2000 J of energy is supplied to the generator, then how much is converted into electrical energy?

2.2 Conduction

FIGURE 2.2.1 Emperor penguin chicks avoid heat loss through conduction by sitting on the adult's feet. In this way they avoid contact with the ice.

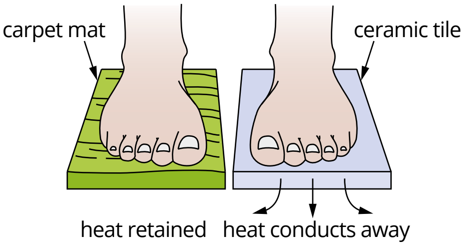


FIGURE 2.2.2 Ceramic floor tiles are good conductors of heat. They conduct heat away from the foot readily and so your feet feel cold on tiles. The carpet mat is a thermal insulator. Thermal energy from the foot is not transferred away as quickly and so your foot doesn't feel as cold.

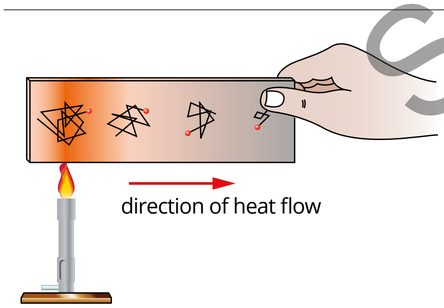


FIGURE 2.2.3 Thermal energy is passed on by collisions between adjacent particles.

If two objects are at different temperatures and are in thermal contact (that is, they can exchange energy via heat processes), then thermal energy will transfer from the hotter object to the cooler object. Figure 2.2.1 shows how, by preventing the chick's thermal contact with the cold ice, this adult penguin is able to protect the vulnerable penguin offspring.

This section focuses on heat transfer by conduction.

CONDUCTORS AND INSULATORS

Conduction is the process by which heat is transferred from one place to another without the net movement of particles (atoms or molecules). Conduction can occur within a material or between materials that are in thermal contact. For example, if one end of a steel rod is placed in a fire, heat will travel along the rod so that the far end of the rod will also heat up; or if a person holds an ice cube, then heat will travel from their hand to the ice.

While all materials will conduct heat to some extent, this process is most significant in solids. It is important in liquids but plays a lesser role in the movement of energy in gases.

Materials that conduct heat readily are referred to as good **conductors**. Materials that are poor conductors of heat are referred to as insulators. An example of a good conductor and a good **insulator** can be seen in Figure 2.2.2.

In secondary-school physics, the terms 'conductor' and 'insulator' are used in the context of both electricity and heating processes. What makes a material a good conductor of heat doesn't necessarily make it a good conductor of electricity. The two types of conduction are related but it's important not to confuse the two processes. A material's ability to conduct heat depends on how conduction occurs within the material.

Conduction can happen in two ways:

- energy transfer through molecular or atomic collisions
- energy transfer by free electrons.

THERMAL TRANSFER BY COLLISION

The kinetic particle model explains that particles in a solid substance are constantly vibrating within the material structure and so interact with neighbouring particles. If one part of the material is heated, then the particles in that region will vibrate more rapidly. Interactions with neighbouring particles will pass on this kinetic energy throughout the system via the bonds between the particles (Figure 2.2.3).

The process can be quite slow since the mass of the particles is relatively large and the vibrational velocities are fairly low. Materials for which this method of conduction is the only means of heat transfer are likely to be poor conductors of heat or even thermal insulators. Materials such as glass, wood and paper are poor conductors of heat.

THERMAL TRANSFER BY FREE ELECTRONS

Some materials, particularly metals, have electrons that are not directly involved in any one particular chemical bond. Therefore, these electrons are free to move throughout the lattice of positive ions.

If a metal is heated, then not only will the positive ions within the metal gain extra energy but so will these free electrons. As the electron's mass is considerably less than the positive ions, even a small energy gain will result in a very large gain in velocity. Consequently, these free electrons provide a means by which heat can be quickly transferred throughout the whole of the material. It is therefore no surprise that metals, which are good electrical conductors because of these free electrons, are also good thermal conductors.

THERMAL CONDUCTIVITY

Thermal conductivity describes the ability of a material to conduct heat. It is temperature dependent and is measured in watts per metre per kelvin ($W\,m^{-1}\,K^{-1}$). Table 2.2.1 highlights the difference in conductivity in metals compared with other substances.

TABLE 2.2.1 Thermal conductivities of some common materials.

Material	Conductivity ($W\,m^{-1}\,K^{-1}$)
silver	420
copper	380
aluminium	240
steel	60
ice	2.2
brick, glass	≈ 1
concrete	≈ 1
water	0.6
human tissue	0.2
wood	0.15
polystyrene	0.08
paper	0.06
fibreglass	0.04
air	0.025

Factors affecting thermal conduction

The rate at which heat is transferred through a system depends on the:

- nature of the material. The larger a material's thermal conductivity, the more rapidly it will conduct heat energy.
- temperature difference between the two objects. A greater temperature difference will result in a faster rate of energy transfer.
- thickness of the material. Thicker materials require a greater number of collisions between particles or movement of electrons to transfer energy from one side to the other.
- surface area. Increasing the surface area relative to the volume of a system increases the number of particles involved in the transfer process, increasing the rate of conduction.

The rate at which heat is transferred is measured in joules per second ($J\,s^{-1}$), or watts (W).

PHYSICSFILE

Igloos

It seems strange that an igloo can keep a person warm when ice is so cold. Igloos are constructed from compressed snow that contains many air pockets. The air in these pockets is a poor conductor of heat, which means heat inside the igloo is not easily transferred away. The body heat of the occupant, as well as that of his or her small heat source, is trapped inside the igloo and is able to keep them warm.

FIGURE 2.2.4 Air pockets in compressed snow enable igloos to keep their occupants warm relative to outside temperatures.

EXTENSION

Thermal conductivity

The rate of energy transfer by conduction (energy per unit time) through a material can be calculated using:

$$\frac{Q}{t}=\frac{kA\Delta T}{L}$$

where $\frac{Q}{t}$ is the heat energy, Q, transferred in joules (J) per unit time, t, in seconds (s)

k is the thermal conductivity of the material ($W\,m^{-1}\,K^{-1}$)

A is the surface area perpendicular to the direction of heat flow, in metres squared (m^2)

ΔT is the temperature difference across the material in kelvin or degrees Celsius (K or °C)

L is the thickness of the material through which the heat is being transferred, in metres (m).

Designers use this relationship when calculating the insulating ability of the fill inside clothing such as parkas. Architects and builders use it to calculate the efficiency of building insulation.

Guidelines exist to ensure the efficiency of insulating materials. Building materials that limit the transfer of heat help to keep houses warm in winter and cool in summer. This saves money and helps to reduce carbon dioxide emissions from the use of gas or electricity to heat houses.

PHYSICS IN ACTION

Passive solar design

Rising energy costs and dwindling resources have caused many countries to try to reduce the amount of fossil fuels used to provide energy for homes, schools and industry.

Passive heating of a building through passive solar design is one way to reduce the overall energy being consumed within the building. Buildings that are designed with passive solar heating and cooling in mind take advantage of natural climate to maintain a comfortable temperature indoors. Figure 2.2.5 describes some of the principles of a passive solar house.

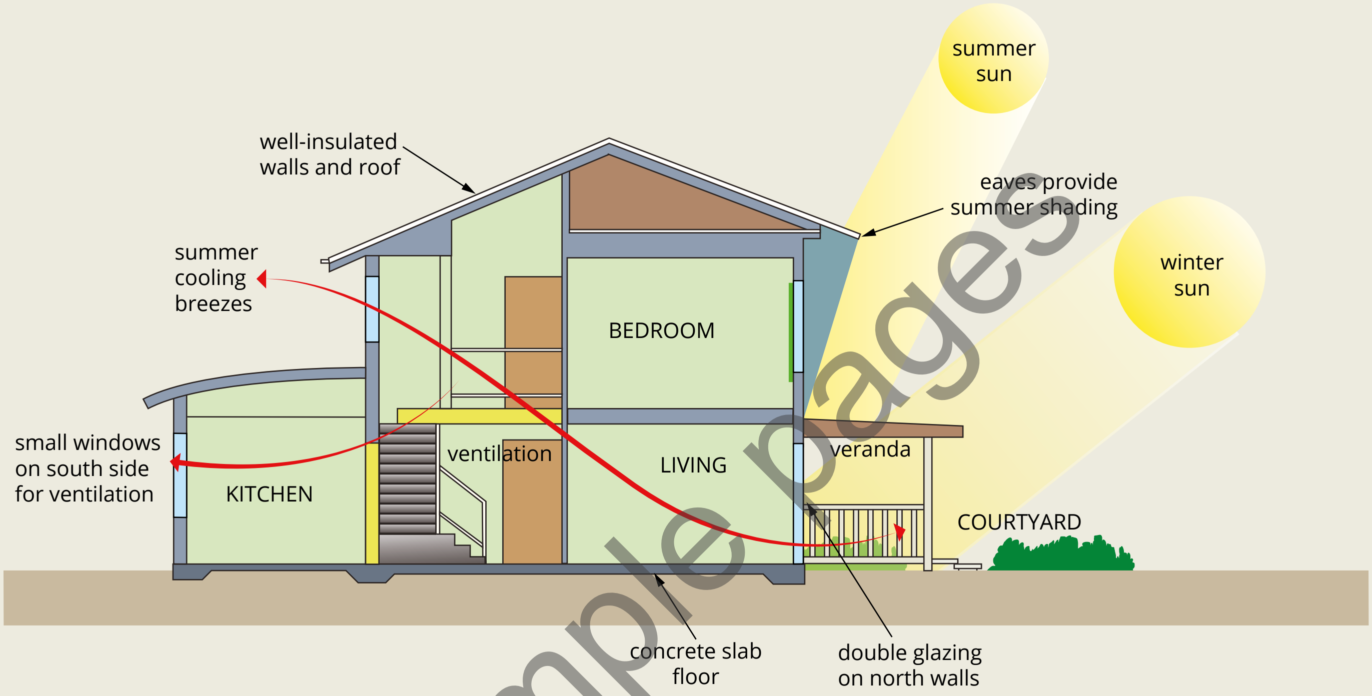


FIGURE 2.2.5 Aspects of good passive solar design applied to housing design can lead to significant energy savings.

Insulation prevents loss by conduction in winter and gain of heat by conduction in summer. Solid brick walls and concrete slab floors provide large amounts of thermal mass, which take longer to heat up on hot days and cool down on cold nights.

Positioning large windows on the northern side of a house allows generous amounts of solar energy to warm the interior in winter. Overhanging eaves and deciduous trees provide shade in summer. Small windows to the south provide ventilation but reduce heat loss on the shady side of the house. Blank walls heavily shaded by trees or overhangs avoid the sun of hot summer afternoons and shield against the prevailing cold westerlies of winter.

Siting living areas on the northern side allows the winter sun to warm areas of the house where it's needed during the day. Rooms that are used little during the day can be sited on the southern side of the house.

Heavy curtains and double-glazing (Figure 2.2.6) can reduce conductive heat loss at night and in winter. They also reduce solar energy gains in summer. Conventional single glazing allows heat to be lost through conduction. Double glazing provides additional thermal resistance by adding a sealed space between two glass panes. The air gap conducts much less heat. Increasingly, argon gas is used to fill the space between the panes instead of air, because it has a lower conductivity than air. Good use of double glazing can reduce heat loss or gain by at least 50%.

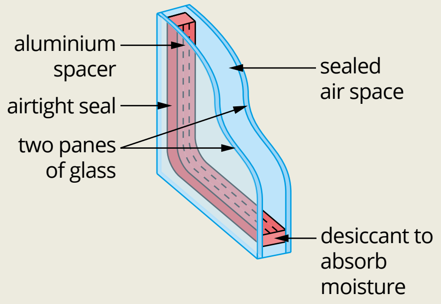


FIGURE 2.2.6 Double-glazed window construction reduces heat loss through windows that would otherwise transfer considerable energy through conduction.

2.2 Review

SUMMARY

- Conduction is the process of heat transfer within a material or between materials without the overall transfer of the substance itself.
- All materials will conduct heat to a greater or lesser degree. Materials that readily conduct heat are called good thermal conductors. Materials that conduct heat poorly are called thermal insulators.
- Whether a material is a good conductor depends on the method of conduction:
  - Heat transfer by molecular collisions alone occurs in poor to very poor conductors.
  - Heat transfer by molecular collisions and free electrons occurs in good to very good conductors.
- The rate of conduction depends on the temperature difference between two materials, the thickness of the material, the surface area and the nature of the material.

KEY QUESTIONS

1. Explain why the process of conduction by molecular collision is slow.
2. Why are metals more likely to conduct heat than wood?
3. List the properties of a material that affect its ability to conduct heat.
4. Stainless steel saucepans are often manufactured with a copper base. What is the most likely reason for this?
5. One way of making a house energy-efficient is to use double-glazed windows. These consist of two panes of glass with air trapped in between the panes. On a hot day, the energy from the hot air outside the house is not able to penetrate the air gap and so the house stays cool.

   Which of the following best explains why double-glazing works?

   A Air is a conductor of heat and so the thermal energy is able to pass through.

   B Air is a conductor of heat and so the thermal energy is not able to pass through.

   C Air is an insulator of heat and so the thermal energy is not able to pass through.

   D Air is an insulator of heat and so the thermal energy is able to pass through.
6. How does a down-filled quilt keep a person warm in winter?
7. Fibreglass insulation batts are thick and lightweight, and they make a house more energy-efficient. On a cold July night, the external temperature in the roof of an insulated house is 6°C. The air temperature near the ceiling inside the house is 20°C. Explain how ceiling insulation decreases energy loss.
8. On a cold day, the plastic or rubber handles of a bicycle feel much warmer than the metal surfaces. Explain this in terms of the thermal conductivity of each material.
9. Explain how windows should be placed on homes to maximise solar gain.
10. What is the main difference between single- and double-glazed windows that makes double-glazed windows better thermal insulators?

2.3 Convection

Convection is the transfer of thermal energy within a fluid (liquid or a gas) by the movement of hot areas from one place to another. Unlike other forms of heat transfer such as conduction and radiation, convection involves the mass movement of particles within a system over a distance that can be quite considerable.

HEATING BY CONVECTION

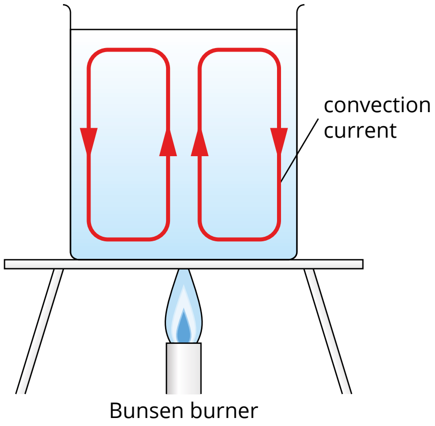


FIGURE 2.3.1 When a liquid or gas is heated, it becomes hotter and less dense so will rise. The colder, denser fluid will fall. As this fluid heats up, it in turn will rise, creating a convection current.

Although liquids and gases are generally not very good conductors of thermal energy, heat can be transferred quite quickly through liquids and gases by convection. Unlike other forms of thermal energy transfer, convection involves the mass movement of particles within a system over a distance.

As a fluid is heated, the particles within it gain kinetic energy and push apart due to the increased vibration of the particles. This causes the density of the heated fluid to decrease and the heated fluid rises. Colder fluid, with slower moving particles, is more dense and heavier and hence falls, moving in to take the place of the warmer fluid. A convection current forms when there is warm fluid rising and cool fluid falling. This action can be seen in Figure 2.3.1. Upwellings in oceans, wind and weather patterns are at least partially due to convection on a very large scale.

It is difficult to quantify the thermal energy transferred via convection but some estimates can be made. The rate at which convection will occur is affected by:

- the temperature difference between the heat source and the convective fluid
- the surface area exposed to the convective fluid.

In a container, the effectiveness of convection in transferring heat depends on the placement of the source of heat. For example, the heating element in a kettle is always found near the bottom of the kettle. From this position, convection currents form throughout the water to heat it more effectively (Figure 2.3.2a). If the heating element were placed near the top of the kettle, convection currents would form only near the top. This is because the hotter water is less dense than the cooler water below and would remain near the top. Convection currents would not form throughout the water (Figure 2.3.2b).

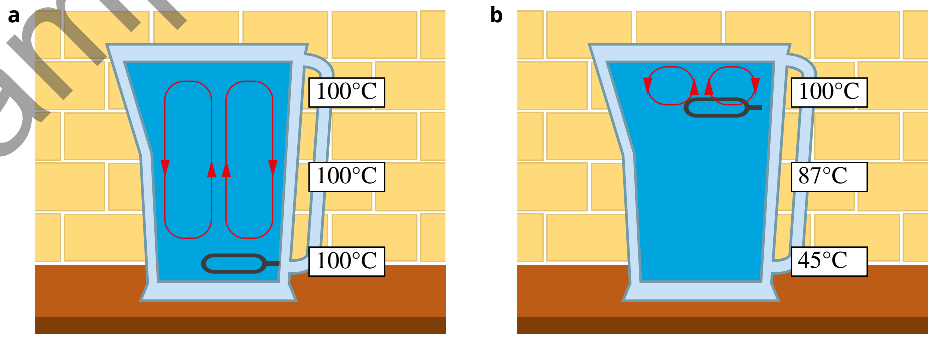


FIGURE 2.3.2 (a) By placing the heating element at the bottom of a kettle, the water near the bottom is heated and rises, forming convection currents throughout the entire depth of the water. (b) If the heating element is placed near the top of the kettle, the convection currents form near the top and heat transfer is slower.

FIGURE 2.3.3 The thunderheads of summer storms are a very visible indication of natural convection in action.

There are two main causes of convection:

- forced convection; for example, ducted heating in which air is heated and then blown into a room
- natural convection, such as that illustrated in Figure 2.3.2, when a fluid rises as it is heated.

A dramatic example of natural convection is the thunderhead clouds of summer storms (Figure 2.3.3), which form when hot, humid air from natural convection currents is carried rapidly upwards into the cooler upper atmosphere.

PHYSICS IN ACTION

Wind chill

Convective effects are the main means of heat transfer that lead to the 'wind chill' factor. The wind blows away the thin layer of relatively still air near the skin that would normally act as a partial insulator in still air. Cooler air comes in closer contact with the skin and heat loss increases. It feels as if the 'effective' temperature of the surrounding air has decreased. Skiers can experience similar effects simply from the wind created by their own motion.

In cold climates the wind chill factor can become an important factor to consider. The chilling effect is even more dramatic when the body or clothing is wet, increasing evaporative cooling (Figure 2.3.4). Evaporation occurs when a liquid becomes a gas, and in the process a large amount of thermal energy is taken away from the remaining liquid. Bushwalkers look for clothing made from materials that dry rapidly after rain and which carry moisture from the perspiration of heavy exertion away from the skin.

FIGURE 2.3.4 In cold environments, such as Antarctica, wind chill factor greatly increases the chilling effect and hence the risk of hypothermia.

PHYSICSFILE

Natural convection in air

There is often a temperature difference between the land and the sea in coastal environments. The temperature of the water hardly changes between night and day due to its high specific heat capacity but the land can become much hotter through the day. As the air over the land is heated, it rises and is replaced by cooler, more dense air from over the sea (Figure 2.3.5). This moving air creates a sea breeze that is experienced in most coastal areas in Australia during summer, including the famous Fremantle Doctor. This makes living on the coast appealing during hot weather.

At night, the process is reversed. The land cools more quickly and so does the air above it. This denser air moves out over the water, displacing the now relatively lighter and warmer air over the sea, and a land breeze is created.

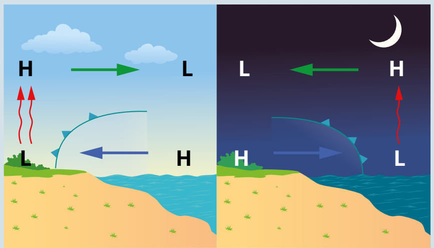


FIGURE 2.3.5 Land and sea breezes are created by convection currents caused by the temperature difference between air over the sea and air over the land. H represents high pressure and L represents low pressure.

2.3 Review

SUMMARY

- Convection is the transfer of heat within a fluid (liquid or gas).
- Convection involves the mass movement of particles within a system over a distance.
- A convection current forms when there is warm fluid rising and cool fluid falling.

KEY QUESTIONS

1 Through what states of matter can convection occur?

2 In which direction does the transfer of heat in a convection current initially flow?

3 Pilots of glider aircraft or hang-gliders, some birds such as eagles and some insects rely on 'thermals' to give them extra lift. Explain how these rising columns of air are established.

4 Compare the conductive and convective abilities of liquids and gases.

5 Convection is a method of heat transfer through fluids. Explain whether it is possible for solids to pass on their heat energy by convection.

6 On a hot day, the top layer of water in a swimming pool can heat up while the lower, deeper parts of the water can remain quite cold. Explain, referring to convection, why this happens.

7 List the steps in the process by which thermal energy is transferred from one place to another within a liquid or gas.

8 What factors affect the rate of thermal convection?

2.4 Radiation

Both convection and conduction involve the transfer of heat through matter. Life on Earth depends upon the transfer of energy from the Sun through the near-vacuum of space. If heat could only be transferred by the action of particles, then the Sun's energy would never reach Earth. Radiation is a means of transfer of heat without the movement of matter.

ELECTROMAGNETIC RADIATION

In this context, **radiation** is a shortened term for electromagnetic radiation, which includes visible, ultraviolet and infrared light. Together with other forms of light, these make up the **electromagnetic spectrum**.

The transfer of heat from one place to another without the movement of particles is by electromagnetic radiation. Electromagnetic radiation travels at the speed of light. When electromagnetic radiation hits an object, it will be partially reflected, partially transmitted and partially **absorbed**. The absorbed part transfers thermal energy to the absorbing object and causes a rise in temperature. When you hold a marshmallow by an open fire, you are using radiation to toast the marshmallow (Figure 2.4.1).

FIGURE 2.4.1 Heat transfer from the flame to the marshmallow is an example of radiation.

Electromagnetic radiation is **emitted** by all objects that are at a temperature above absolute zero (0 K or −273°C). The **wavelength** and **frequency** of the emitted radiation depends on the internal energy of the object. As temperature is related to the internal energy of an object, the higher the temperature of the object, the higher the frequency and the shorter the wavelength of the radiation emitted. This can be seen in Figure 2.4.2.

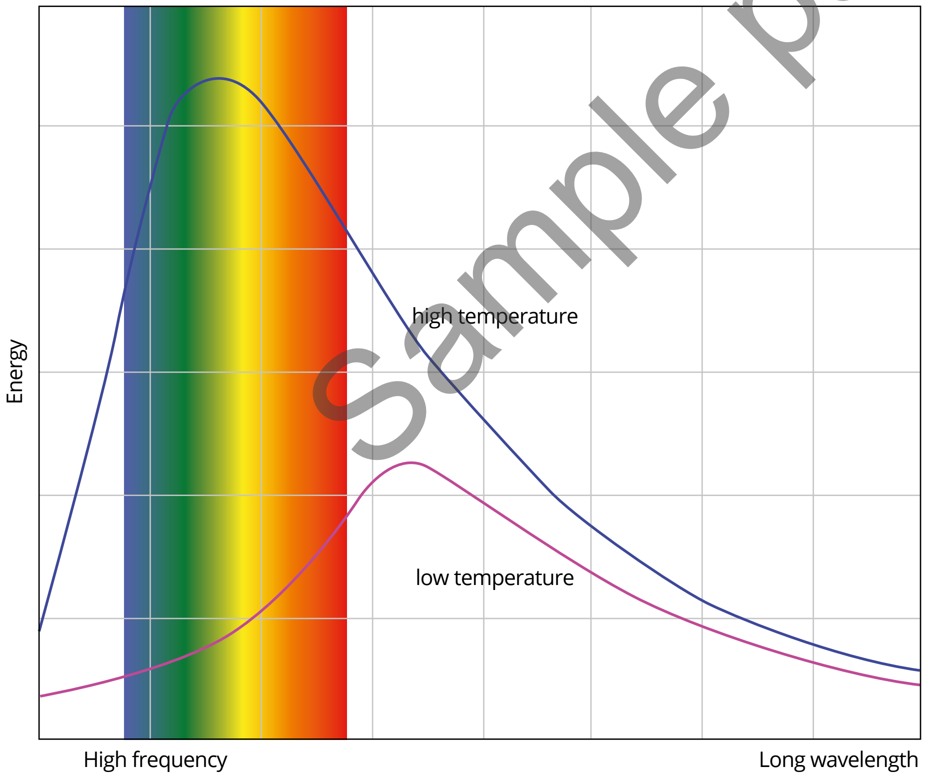


FIGURE 2.4.2 A system emits radiation over a range of frequencies. At a low temperature, it will emit small amounts of radiation of longer wavelengths. As the temperature of the system increases, more short-wavelength radiation is emitted and the total radiant energy emitted increases.

A human body emits radiation in the infrared range of wavelengths, while hotter objects emit radiation of a higher frequency and shorter wavelength. Hotter objects can emit radiation in the range of visible, ultraviolet and shorter wavelengths of the electromagnetic spectrum. For example, as a red-hot fire poker heats up further, it becomes yellow-hot.

EMISSION AND ABSORPTION OF RADIANT ENERGY

FIGURE 2.4.3 The silvered surface of an emergency blanket reflects thermal energy back to the body, and retains the radiant energy, which would normally be lost. This simple method works as excellent thermal insulation.

All objects both absorb and emit thermal energy by radiation. If an object absorbs more thermal energy than it emits, its temperature will increase. If an object emits more energy than it absorbs, its temperature will decrease. If no temperature change occurs, the object and its surroundings are in thermal equilibrium.

While all objects emit some radiation, they will not all emit or absorb at the same rate.

A number of factors affect both the rate of emission and the rate of absorption.

- Surface area—the larger the exposed surface area, the higher the rate of radiant transfer.
- Temperature—the greater the difference between the temperature of the absorbing or emitting surface and the temperature of the surrounding objects, the greater the rate of energy transfer by radiation.
- Wavelength of the **incident** radiation—matte black surfaces are almost perfect absorbers of radiant energy at all wavelengths. Highly reflective surfaces are good reflectors of all wavelengths. An example of how reflective surfaces can be exploited is shown in Figure 2.4.3. For all other surfaces, the absorption of particular wavelengths of radiant energy will be affected by the wavelength of that energy. For example, although white surfaces absorb visible wavelengths of radiant energy poorly, white surfaces will absorb infrared radiation just as well as black surfaces do.
- Surface colour and texture—the characteristics of the surface itself determine how readily that particular surface will emit or absorb radiant energy.

Matte black surfaces will absorb and emit radiant energy faster than shiny, white surfaces. This means that a roughened, dark surface will heat up faster than a shiny, light one. Matte black objects will also cool down faster since they will radiate energy just as efficiently as they absorb energy. Car radiators are painted black to increase the emission by radiation of the thermal energy that is collected from the car engine. A silvered surface will reflect radiant energy, taking longer to heat up.

PHYSICSFILE

Thermal imaging

All objects emit radiant energy. Humans are warm-blooded and emit radiation in the infrared region of the electromagnetic spectrum (Figure 2.4.4). This radiation is not visible to you, but can be detected using thermal imaging devices or night-vision goggles. These devices are used by the military for surveillance, and by search and rescue personnel. Some animals, notably some varieties of bugs, are able to detect infrared radiation.

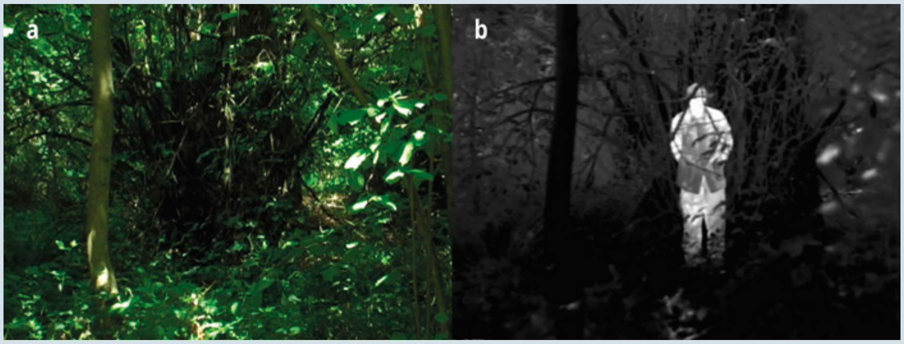


FIGURE 2.4.4 This person is difficult to see using the visible range of the electromagnetic spectrum (a), but they are warmer than the trees surrounding them and produce a stronger infrared emission, which the thermal imaging device is able to detect (b).

PHYSICSFILE

Heat loss in humans

It is estimated that, at normal room temperature, about 50% of a person's heat loss is by radiation.

PHYSICS IN ACTION

Engine cooling systems in cars

Have you ever noticed the heat coming off a car engine after a journey? If not, next time you go for a drive, hold your hand over the engine at the end of the journey and notice how hot it is.

This is because a car engine is not 100% efficient. In fact, only about 20–30% of the chemical energy contained within the fuel is transformed into mechanical energy needed to drive the car. The rest of the energy released when the fuel burns inside a car engine is lost as thermal energy.

A car engine does need some heat to keep it running smoothly and reduce wear on the parts. The rest of the heat has to be removed to avoid the engine overheating. This thermal energy is removed by the car engine's cooling system.

A car's cooling system works by circulating a fluid, called a coolant, in pipes around the engine. This coolant absorbs some of the thermal energy generated during combustion of the fuel in the engine. As the hot coolant is pumped away from the engine, it removes thermal energy, regulating the engine temperature.

The hot coolant is then passed through a heat exchanger, called a radiator (Figure 2.4.5). The radiator is a system of narrow tubes, which gives it a high surface area. A greater surface area means more energy can be radiated. Air from outside the car is blown across these pipes. This air can be moved across the radiator either by a fan or just by using the airflow over the moving car.

As the air is blown across the radiator, thermal energy is transferred from the coolant to the air. The air heats up and the coolant cools down. The coolant is then recirculated around the engine to continue the cooling process.

FIGURE 2.4.5 A radiator is often placed at the front of the car where it can take advantage of the airflow over the moving car.

PHYSICS IN ACTION

Solar water heating

The Sun's energy falls on the Earth's surface at the rate of about 3.6 MJ on each square metre per hour. This means that an average roof of around 200 m^2 receives 3600 MJ (or 3.6 GJ) of energy in 5 hours of sunlight. Given that an average household might use around 72 MJ of electrical energy in a day you can see the possibilities!

You can make use of this free source of energy by using solar cells (also called photovoltaic cells), which transform radiant energy from the Sun into electrical energy. Another much simpler way to harness the energy from the Sun is to use it to heat water.

If you have ever used a solar camp shower, you have taken advantage of solar hot water. A solar camp shower is black plastic container filled with water and hung out in the sunshine. Recall that darker surfaces absorb more radiant energy than lighter surfaces. The black plastic absorbs radiant energy from the Sun and this energy is converted to thermal energy. This thermal energy heats the water inside.

The solar hot-water systems used in homes around Australia and countries such as Spain, China and India work on similar principles. A solar collector panel is placed on the sunniest side of the roof and connected to a water storage tank.

The solar collector is usually made up of dark-coloured pipes that allow the flow of a fluid. In warmer climates, such as Australia, the fluid is regular drinking water, which becomes the hot water used within the home. In cooler climates, the fluid is often a mix of water and antifreeze, which stops the water freezing in the pipes. This water/antifreeze mixture is pumped through a water storage tank in closed pipes, where it transfers the thermal energy to the hot water for the house.

There are two main types of solar water heaters: passive and active. Active solar water heaters use electrical pumps to move the hot water around the system. Passive systems (Figure 2.4.6) rely on convection currents to move the hot water. The natural convective currents can be a low-energy means of moving hot water from a solar collector to a storage tank without the use of an electric pump. A simple passive system is shown in the diagram below.

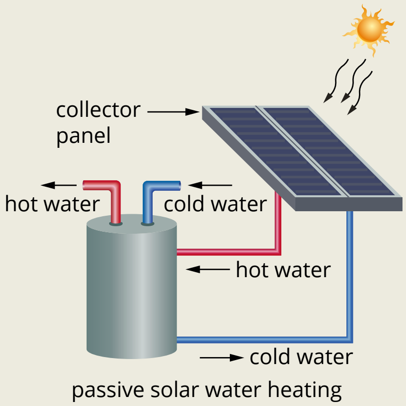


FIGURE 2.4.6 A simple passive solar hot-water system.

2.4 Review

SUMMARY

- Any object whose temperature is greater than absolute zero emits thermal energy by radiation.
- Radiant transfer of thermal energy from one place to another occurs by means of electromagnetic waves.
- When electromagnetic radiation falls on an object, it will be partially reflected, partially transmitted and partially absorbed.
- The rate of emission or absorption of radiant heat will depend upon the:
  - temperature difference between the object and the surrounding environment
  - surface area and surface characteristics of the object
  - wavelength of the radiation.

KEY QUESTIONS

1 Light is shone on an object.

  a List three interactions that can occur between the light and the object.

  b Which of the interactions from part (a) are associated with a rise in temperature?

2 The wavelength and frequency of emitted radiation depend on the internal energy of an object. Complete the sentences below by choosing the correct option from those provided in brackets.

  The higher the temperature of the object, the [**higher**/**lower**] the frequency and the [**longer**/**shorter**] the wavelength of the radiation emitted. For example, if a particular object emits radiation in the visible range, a cooler object could emit light in the [**infrared**/**ultraviolet**] range of the electromagnetic spectrum.

3 Which of the following will affect the rate at which an object radiates thermal energy?

  A its temperature

  B its colour

  C its surface nature (shiny or dull)

  D none of these

  E all of A–C

4 Why is it impossible for heat to travel from the Sun to the Earth by conduction or convection?

5 Thermal imaging technology can be used to locate people lost in the Australian bush. How can thermal imaging technology ‘see’ people when the human eye cannot?

6 Three identical, sealed beakers are filled with near-boiling water. One beaker is painted matte black, one is dull white and the third is gloss white.

  a Which beaker will cool fastest?

  b Which beaker will cool slowest?

7 Computer chips generate a lot of thermal energy that must be dispersed for a computer to function efficiently. Devices called heat sinks are used to help this process. Suggest what properties of a material would make it a good heat sink.

Chapter review

02

KEY TERMS

absorption
conduction
conductor
convection
electromagnetic spectrum
emission
emitted
evaporation
frequency
incident
insulator
internal energy
passive heating
radiation
wavelength

The following information applies to questions 1 and 2.
A household is considering changing from traditional incandescent lighting to LEDs. Refer to the respective percentage efficiencies from Table 2.1.1 on page 30.

1 Calculate the electrical energy effectively converted to light for each 1 kJ supplied for:
  - **a** an incandescent light
  - **b** an LED.

2 How much more does an incandescent light cost to run than an LED light?

The following information applies to questions 3–6.
A student places a heating element and an electric whisk in an insulated container with 200 mL of water initially at 20.0°C, which is open at the top. He calculates that the heater adds 1850 J of heat energy to the water, and the whisk does 520 J of work on the water.

3 What is the total potential change in internal energy of the water?

4 If there was no heat loss from the container, calculate the final temperature the water would be expected to reach. Use $c_{water} = 4180\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$.

5 The student measured the final temperature and found it to only be 21.50°C due to losses to the air through the open top. How much of the energy supplied by the whisk and heater remained to increase the internal energy of the water?

6 Calculate the efficiency of the whisk and heater in heating the water once heat losses to the air are taken into account.

7 Two different objects are in thermal contact with each other. The objects are at different temperatures. What do the temperatures of the two objects determine?
  - **A** The process by which thermal energy is transferred.
  - **B** The heat capacity of each object.
  - **C** The direction of transfer of thermal energy between the objects.
  - **D** The amount of internal energy in each object.

8 Thermal energy may be transferred:
  - **a** in a fluid as a result of density changes of the fluid
  - **b** in a non-metallic substance as a result of lattice vibrations.

Which process—conduction, convection or radiation—applies to each energy transfer?

9 Suppose you are sitting next to a fireplace in which there is a fire burning. One end of a metal poker has been left in the fire. Explain:
  - **a** why you eventually feel the handle of the poker get hot
  - **b** why you feel warm
  - **c** how heat is lost from the room.

10 The interior of a thermos bottle is silvered to minimise heat transfer due to which one or more of the following processes: conduction, convection or radiation?

11 A house is fitted with an electric heater in one corner in order to heat a whole room. By which process or processes (conduction, convection or radiation) is the room heated when the heater is in operation?

12 The Sun continuously radiates energy into space, some of which reaches the Earth. The average temperature of the surface of the Earth remains about 300 K. Over the short term, why doesn't the average global temperature rise as the Sun's energy reaches it?

13 Explain the function of the evacuated enclosure between the walls of a vacuum flask.

14 Describe an experiment that would prove that a shiny, white surface is a poorer absorber of heat radiation than a dull or black surface. Explain one way this fact is used in everyday life.

15 A premature baby in an incubator can be dangerously cooled even when the air temperature in an incubator is warm. Explain why.

16 If you are lost in the snow, you are advised to build yourself a snow cave. In terms of thermal conductivity, explain how it is possible to stay warm inside a cave made of snow or ice.

The following information applies to questions 17 and 18.

An aluminium can with a paper label is left in a deep freeze for some time. On taking the can out of the freezer, your hand sticks to the cold aluminium but not the label.

17 Which surface, paper or can, will be at the lower temperature?

18 The label is peeled off the can. Which item, paper or can, will return to normal room temperature first? Explain.

19 Design a system for a hot water storage tank that would permit hot water to be taken from the tank and replacement cold water to enter without the two mixing. Include in your design appropriate connections to allow the water to be circulated without the need for pumps.

20 A day will feel warm if the air is at 24°C. However, a pool at 24°C will feel quite cool when swimming. Explain, using your understanding of heat processes, why this is the case.